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A survey on exposure-response relationships for road, rail, and aircraft noise annoyance: Differences between continuous and intermittent noise

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ABSTRACT

The aim of the present study is to establish exposure-response relationships reflecting the percentage highly annoyed (%HA) as functions of road traffic, railway, and aircraft noise exposure, measured as day-evening-night level (Lden), as well as to elucidate the degree to which the acoustic indicator Intermittency Ratio (IR), which reflects the “eventfulness” of a noise situation, predicts noise annoyance. We conducted a mixed-mode representative population survey in a stratified random sample of 5592 residents exposed to transportation noise all over Switzerland. Source-specific noise exposure was calculated for each floor and each façade based on comprehensive traffic data. Noise annoyance was measured using the ICBEN 11-point scale. The survey was carried out in 4 waves at different times of the year. We hypothesized that in addition to Lden, the effects of noise on annoyance can be better explained when also considering the intensity of short-term variations of noise level over time. We therefore incorporated the acoustic indicator IR in the statistical models. For all noise sources, results revealed significant associations between Lden and %HA after controlling for confounders and independent predictors such as IR (measured over 24 h), exposure to other transportation noise sources, sex and age, language, home ownership, education level, living duration, temperature, and access to a quiet side of the dwelling. Aircraft noise annoyance scored markedly higher than annoyance to railway and road traffic noise at the same Lden level. Railway noise elicited higher percentages of highly annoyed persons than road traffic noise. Results furthermore suggest that for road traffic noise, IR has an additional effect on %HA and can explain shifts of the exposure-response curve of up to about 6 dB between low IR and high IR exposure situations, possibly due to the effect of different durations of noise-free intervals between events. For railway and aircraft noise annoyance, the predictive value of IR was limited.

1. Introduction

Besides sleep disturbances, annoyance is one of the most widespread immediate effects of transportation noise exposure, responsible for a considerable proportion of healthy life years lost due to noise (WHO, 2011). Noise annoyance can be viewed as a multi-faceted stress reaction involving individual physiological, emotional, cognitive, and behavioral responses which can partly be remembered and be integrated into a verbally expressed annoyance response (Guski et al., 2017). Noise annoyance has also shown to be a relevant effect modifier for the risk of hypertension (Babisch et al., 2013) and was observed to be associated with subsequent lower levels of physical activity (Foraster et al., 2016), which again may act in the long run as a precursor of increasing cardiovascular disease risks. Because noise annoyance develops in considerably less time than somatic disease, annoyance could be considered as an early warning signal for other more severe health risks. Annoyance therefore has always played a pivotal role in the setting of noise exposure limits. In the population, the risk to be highly annoyed by noise is many times higher than noise-induced somatic disease risks, and thus the percentage of people “highly annoyed” (%

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HA) can reliably be estimated also at low exposure levels and in smaller population samples. The apparent shift of the exposure-response relationships towards increasing annoyance, most convincingly demonstrated for aircraft noise (Babisch et al., 2009; Brink et al., 2008b), is an important rationale to regularly re-investigate the relationship between transportation noise exposure and annoyance effects to inform public health and noise abatement policy. To this end, the present study investigated annoyance to road, rail and air traffic in a survey based on a stratified random sample of the entire Swiss population. The main aim of the survey was to establish exposure-response relationships reflecting the percentage highly annoyed (%HA) as functions of road traffic, railway, and aircraft noise exposure, measured as day-evening-night level (Lden), as well as to quantify differences in %HA between continuous and intermittent noise exposure situations. Furthermore, the study aimed at identifying additional relevant predictors of noise annoyance and elucidate their relative contribution to the generation of annoyance reactions. The survey was carried out in the framework of the interdisciplinary SiRENE project which investigates acute, short- and long-term effects of transportation noise exposure on annoyance, sleep disturbances and cardiometabolic risks (Eze et al., 2017; Foraster et al., 2016; Heritier et al., 2017; Karipidis et al., 2014; Röösli et al., 2017; Rudzik et al., 2018; Thiesse et al., 2018; Wunderli et al., 2015).

Typically, annoyance surveys consider noise exposure only as equivalent continuous sound pressure levels over longer time periods (predominantly by using energy-based average metrics like the Ldn, Lden, LNight or LDay). However, it has been suggested that noise effects may be more thoroughly explained when considering other factors in addition to the average energetic amount of noise. These include the variation of noise level over time, which can influence attention to sounds and eventually annoyance (Bockstael et al., 2011; Botteldooren et al., 2008), noticeability of sounds (De Coensel et al., 2009; Schomer and Wagner, 1996), or the maximum sound pressure level and the rise time of levels of noise events in the case of noise-induced awakening (Basner et al., 2011; Basner et al., 2006) or motility reactions (Brink et al., 2008a) during sleep. Normally, measurements of transportation noise sources made over a certain time period include transient high-amplitude noise events, which contribute to the Leq energetically, but do not account for the discontinuous "peaking" nature of noise. In rather intermittent – as opposed to continuous – noise situations, such events are characterized by maximum sound pressure levels that clearly stand out from background noise, with relatively calm periods in between. Situations with intermittent noise are characterized by dominant single events which are likely to cause higher attention to the noise source, and therefore may increase annoyance. The same situations, on the other hand, feature longer periods of relative quietness and as such might have the opposite effect and reduce annoyance. It is currently unknown which of the two aspects of intermittency better explains differences in annoyance responses. To reflect the intermittent nature of a noise exposure situation, we developed the acoustical indicator Intermittency Ratio (IR), which expresses intermittency as the energetic contribution of individual noise events relative to the total sound energy in a given measurement period (Wunderli et al., 2015). We used IR as a complementary exposure metric in addition to long-term Lden to investigate the extent to which annoyance reactions are associated with (a) average exposure to the noise sources road, rail and air traffic, and (b) the intermittency characteristic of the noise exposure.

2. Methods

2.1. Study population and survey procedure

The study population comprised all officially registered residents in Switzerland in the age range between 19 and 75 years with known home address and known location of their dwelling/apartment, including floor. From this population, a stratified random sample of residents all over the country was drawn based on exposure strata for road traffic, railway and aircraft noise described in more detail below.

For the survey, we implemented a mixed-mode approach using postal questionnaires and offering the option for completion of the survey online. The postal survey consisted of a folded seven-page long questionnaire booklet, mailed together with an accompanying letter that stated purpose of the research, funding sources, and link to the online version. Addressees were explicitly informed that their participation in the survey was also welcome, if they "do not have any noise at home". As the survey was carried out in all three language regions in Switzerland, we produced three different language versions (German, French, and Italian). To be able to control for seasonal effects, the survey was carried out in 4 waves, which were spaced 3 months apart. The bulk mailing dates of these waves were 18 Nov 2014, 11 Feb 2015, 08 May 2015, and 17 Aug 2015. Based on previous sample size calculations (Brink et al., 2016) and expecting a response rate of at least 25%, we posted 4 × 4500 questionnaires to individual addressees. Non-responders were reminded one time with a reminder card sent approx. one month after the initial mailing.

In order to assess a potential non-response bias with respect to the distributions of noise exposure, age, noise annoyance, general noise sensitivity, pro-environmental attitude and education level, we carried out a non-responder telephone survey one month after the mail-out of Wave 3. For this we conducted 224 computer assisted brief (average 3 min) telephone interviews among initial non-responders of that wave, of which fixed line telephone numbers could be retrieved using a matching algorithm (N = 2859). For the non-responder interviews, we defined a minimum target number of interviews to be completed (N ≥ 200). Retrieved telephone numbers were randomly called until the non-responder sample size was reached.

The survey protocol was approved by the Cantonal ethics commission of Bern and conformed to the tenets of the Declaration of Helsinki.

2.2. Questionnaire

Noise annoyance was assessed source by source with both the 5-point verbal ICBEN scale with the verbal marks "not at all", "slightly", "moderately", "very", "extremely", as well as the 11-point numerical ICBEN scale (Fields et al., 2001). However, all analyses related to annoyance reported in this article pertain to the 11-point scale as this scale is less prone for divergent semantic interpretations of the numerical scale points across the three different languages used for the survey. Ticking one of the three top scale points on the 11-point scale (8, 9, or 10, corresponding to 28% of the scale length) defined "highly annoyed" (HA) status.

Further parts of the questionnaire were dedicated to dwelling situation, time use, sleep disturbances, sleeping habits, window opening behavior, pro-environmental attitude (positive attitude towards environmental protection), coping styles using the BriefCOPE inventory (Carver, 1997), coping with noise strategies, locus of control using the IE4 (Kovaleva et al., 2012), resilience as measured with the RS-11 (Schumacher et al., 2005), mental health as measured with the SF36 subscale 'Mental Health' (Bullinger and Kirchberger, 2011), general health and other health-related questions, smoking habits, physical activity, and questions on occupation and educational attainment. Noise sensitivity was assessed with a single item as well as with the 13-item NoiSeQ-R instrument (Griefahn et al., 2007).

2.3. Noise exposure assessment

Transportation noise exposure calculations were carried out as part of the SiRENE project within the "sonBASE" framework, the Swiss national noise monitoring database (Federal Office for the Environment, 2018). sonBASE integrates a standardized nation-wide inventory of the exposure from transportation noise sources. Building footprints in the database are subdivided into dwelling units, which are located on and assigned to floors. The dwelling units are linked to the register of houses and dwellings, maintained by the Swiss Federal Statistical Office (BFS), including register data of individual residents such as name, year of birth, and gender. The exposure calculations in the SiRENE project were carried out for the reference year 2011 and encompassed all transportation noise sources, i.e. all roads, railway tracks and airports, and all registered Swiss buildings (about 1.8 Mio.). Exposure to each noise source (road, rail, and air traffic) was separately calculated for a total of about 54 Mio. façade points using traffic data as input to comprehensive Swiss noise calculation models (Empa, 2010; Heutschi, 2004; Wunderli, 2012). Noise exposure was calculated for up to 3 façade points per building façade and floor in 24 one-hour time slices that comprised the 1-hour LAeq, the number of noise events, and the new metric IR. This allowed the calculation of any kind of noise metric for the most exposed or least exposed façade, as well as the corresponding IR over different time periods (IR_{Day}, IR_{Night}, IR_{24h}). Further details regarding exposure assessment are described in (Karipidis et al., 2014).

2.4. Calculation of the Intermittency Ratio (IR)

Highly intermittent transportation noise consists of subsequent pass-bys of vehicles (cars or trucks, aircraft, trains etc.) which acoustically stand out from the background (noise) by a certain degree. We define such parts of the level-time course as “noise events”. For an integral characterization of the “eventfulness” of an exposure situation over a longer period of time we introduce the event-based sound pressure level $L_{eq,T,Events}$, which accounts for all sound energy contributions that exceed a given threshold. This $L_{eq,T,Events}$ can now be compared to the overall (total) sound pressure level $L_{eq,T,tot}$, i.e., the average level of all noise sources that acoustically account for a particular exposure situation. The Intermittency Ratio IR is defined as the ratio of the event-based sound energy to the overall sound energy:

$$IR = \frac{10^{0.1\times L_{eq,T,Events}}}{10^{0.1\times L_{eq,T,tot}}} \times 100 = 10^{0.1\times(L_{eq,T,Events}-L_{eq,T,tot})} \times 100\ [\%] \quad (1)$$

A single event only contributes to $L_{eq,T,Events}$ if its level exceeds a given threshold K:

$$K \equiv L_{eq,T,tot} + C\ [dB] \quad (2)$$

The threshold K is defined relative to the long-term average $L_{eq,T,tot}$ and an offset C. Based on numerical simulations of various traffic situations, it was set to C = 3 dB. By definition, IR only takes values between 0 and 100% (including 0% and 100%). An IR of higher than 50% means that more than half of the total sound dose is caused by “distinct” pass-by events. In situations that only consist of events that clearly emerge from background noise (e.g. a receiver point near a railway track), IR can get close to 100%. In contrast, constantly flowing road traffic, e.g. from a distant motorway, only yields small IR values.

We hypothesized that IR is useful in characterizing the different forms of, particularly, road traffic noise, from highly intermittent small city streets to motorways that display an almost constant flow of traffic. The calculation principle of the IR metric is documented in more detail in (Wunderli et al., 2015).

2.5. Factorial design and sampling

The initial noise exposure calculation for the year 2011 described above provided the sampling frame for the survey. The factorial design accounted for three sources (road, rail, air), two time periods ($L_{Aeq,16h,Day}$ and $L_{Aeq,08h,Night}$), three categories of IR (low: 0–33%, medium: 33–66%, high: 66–100%) in these respective time periods, and ten 2.5 dB wide Leq exposure categories in the range between < 45 dB(A) and > 65 dB(A) for the day period, and between < 35 dB(A) and > 55 dB(A) for the night period. This resulted in a design with 3 × 2 × 3 × 10 = 180 factor level combinations (cp. Supplementary table T2). For each cell of the design, we randomly (and nation-wide) selected 100 dwelling units and corresponding individual (postal) addresses (25 per survey wave). For the cell assignment, the sampling algorithm randomly decided if the façade point with the highest or lowest sound pressure level of a sampled dwelling unit determined cell membership. It is important to note that even if a dwelling unit was e.g. assigned to the source and time period “aircraft noise at day”, ultimately the exposure data for all sources and time periods at all façade points of the same dwelling unit were also obtained (if exposure values were available). This allowed calculation of multi-exposure models (for up to three sources).

2.6. Statistical analysis

All questionnaire variable values were checked for plausibility and were corrected if deemed necessary. Individual noise exposure was reassigned based on the correct floor information indicated by the respondents, where necessary. Respondents were asked at the beginning of the questionnaire or online survey if they lived for the most part of their time at the address the questionnaire was sent to (and noise exposure was calculated for). Respondents answering no to this question (N = 147) were excluded. Missing item values in multi-item scales were replaced at the item level prior to calculating the scale or subscale score, by imputing the missing item value if at least 50% of the items of the respective scale or subscale values were present. Missing item values were imputed using single stochastic regression imputation. Aside from the multi-item scales in the present study, particularly, the NoiSeQ-R, no other missing values in any other variable were imputed.

A potential non-response bias was investigated by testing differences between the 5592 original responders and 224 randomly drawn non-responders, by comparing answers of the two groups to a few key questions from the original questionnaire. Differences were tested with the nonparametric Mann-Whitney-*U* Test.

For the modeling of exposure-response associations, noise exposure is expressed as Lden using the time bins 07 h–19 h (day), 19 h–23 h (evening), and 23 h–07 h (night). We also calculated for each façade point per dwelling unit LDay, LNight, as well as IR over 24 h, further referred to as $IR_{24h.}$ The statistical models account for the façade point with the highest Lden at the respondent's dwelling and the corresponding IR_{24h} value at that same façade point. It is important to note that this is not necessarily also the façade point with the highest IR_{24h} of the dwelling. Cases with too little or no calculated exposure were truncated to predefined values of 30 dB(A) Lden and 20 dB(A) LNight respectively. Truncated cases for the primary source were entirely excluded from modeling exposure-response relationships of that source. This procedure resulted in 5431 eligible cases for road traffic noise (as primary source), 3536 cases for railway noise (as primary source), and 3097 cases for aircraft noise (as primary source).

Average day and night air temperatures during a 90 day period before the date the questionnaire was filled-out were individually assigned to each respondent, based on data from the respondent's nearest weather station operated by the Federal Office of Meteorology and Climatology (MeteoSwiss). The data were used to estimate the effect of outside air temperature in the statistical models.

Statistical modeling basically pursued a predictive goal, rather than an explanatory one (Shmueli, 2010). All models were calculated separately for each primary noise source (road, rail, or air) and aimed at predicting the probability to be highly annoyed (P_{HA}) as a function of Lden, IR and a range of other independent variables (confounders and other predictors, some binary, some continuous). It should be emphasized that all variables considered in the modeling have been previously demonstrated to be related to and/or were considered to conceptually have a potential association with annoyance. Independent variables to condition on in order to reduce the risk of biased estimates were identified in an iterative process using directed acyclic graphs (Greenland et al., 1999; Shrier and Platt, 2008). In a previously published article by the SiRENE study group, a reversed U-shaped relationship between IR_{Night} and cardiovascular mortality risks was observed insofar as the risks were higher for midrange IR values than for very low or very high IR in a multipollutant (but dominated by road traffic noise) model (Heritier et al., 2017). We therefore decided to a priori use both linear and quadratic terms of IR_{24h} in the models. For all model specifications, the probability to be highly annoyed (P_{HA}) was estimated using the generalized linear model. The modeling proceeded in stages: First, we explored crude models (further referred to as "Model 0") where the binary variable HA is regressed on Lden. Second, we included the façade-point-corresponding IR_{24h} and IR_{24h}^2 of the primary noise source ("Model 1"). Then we built multi-pollutant models combining the Lden and the two IR variables of the source for which the annoyance response was obtained with the Lden of the remaining two sources ("Model 2"). We then built an strictly causal (as opposed to predictive) model ("Model 3") for the associaton between Lden and the probability to be highly annoyed by adjusting for the confounders gender, age and age^2, as previous research suggests an inverted U-shaped pattern for age, where the largest number of highly annoyed individuals was found in the middle-aged segment of the population (Van Gerven et al., 2009), language group (here: Germanic [German] vs. Romanic [French or Italian]), home ownership, and highest level of education (as expressed from 1 = primary school finished to 13 = doctorate received). The fifth model ("Model 4") combined the predictors from Model 2 and Model 3. A last "full model" ("Model 5") controlled for additional independent predictors: It included the duration of years lived in the dwelling, the average day air temperature measured over three months before the date of fill out, the interview mode (postal vs. online), and the difference between the maximum façade point of the exposure to the primary source and the energetic sum of the road and railway noise Lden at the façade point where this sum was minimal. This variable expresses the potential benefit of availability of a less noise-exposed side of the dwelling, for example, by having a sleeping room on the quiet side. We hypothesized that this difference is negatively associated with the probability to be highly annoyed (de Kluizenaar et al., 2011). This last group of variables (together with IR and exposure from the non-primary sources) could also have been regarded as effect modifiers and stratified for in the analysis. However, we opted against this because we were less interested in the way these variables affect slope or direction of the relationship between Lden and annoyance, but were rather interested in their overall contribution to annoyance and their predictive power within the full model.

The Nagelkerke pseudo R^2 statistic is reported for all model specifications to provide an indication of explained variance of the models. Goodness of fit was estimated with the Akaike Information Criterion (Akaike, 1974) and the Hosmer-Lemeshow test (Hosmer and Lemeshow, 2013).

Statistical significance was considered at an alpha level of 0.05. Analyses were performed with R version 3.5.1 (The R Foundation for Statistical Computing) and SPSS Statistics version 24 (IBM Corp.).

3. Results

3.1. Response

From the originally 18,000 questionnaires/cover letters sent out, 5592 (31%) were returned of which 21% of the respondents completed the questionnaire online. General response statistics are given in Supplementary table T1. A detailed breakdown of the response rates by source, time period, LDay category, LNight category, and IR_{24h} category is presented in Supplementary table T2.

3.2. Distribution of exposure characteristics in the sample

Fig. 1 shows the frequency distribution of Lden (upper panel) and IR_{24h} (lower panel) for the eligible cases for each primary noise source.

Supplementary table T3 shows the number of available minimum (lowest) and maximum (loudest) façade exposure values across all three sources for all eligible cases in the sample (N = 5445), calculated for LDay and LNight.

We inspected the relationships between L_{den} and corresponding IR_{24h} at the loudest façade point in the sample and found that correlation between IR_{24h} and Lden was present for all noise sources, with

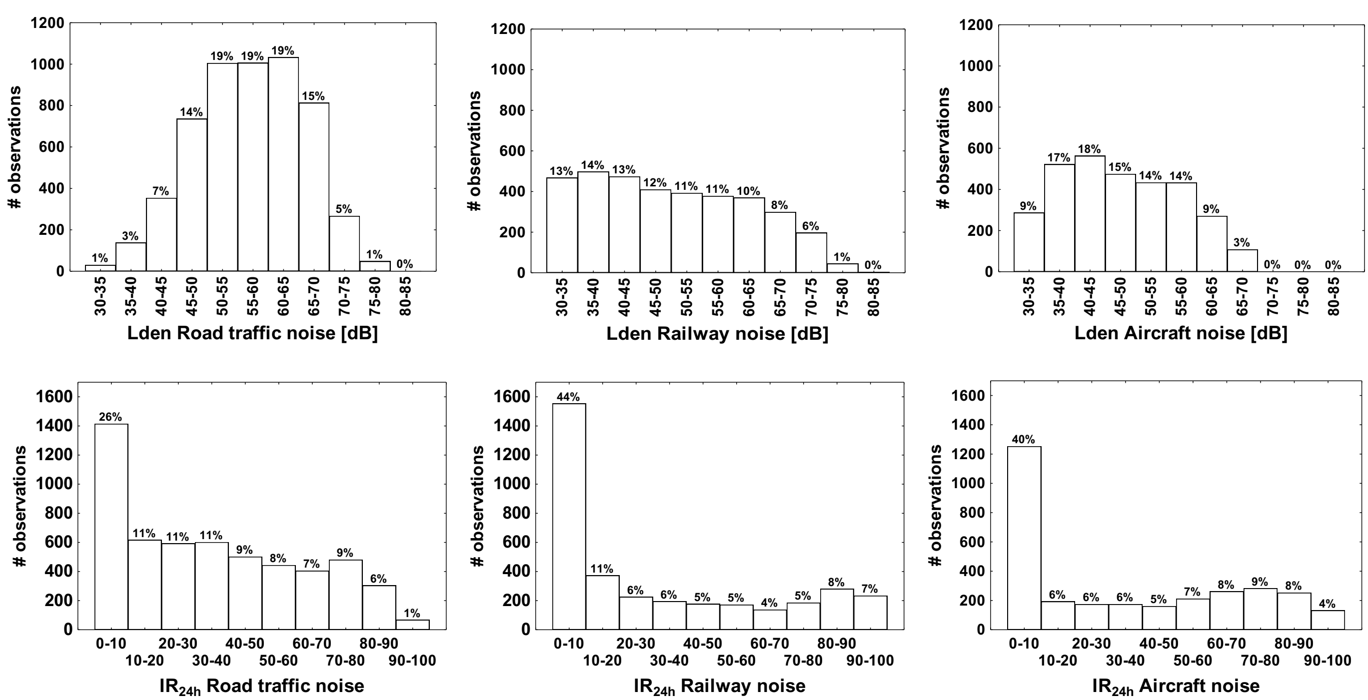

Fig. 1. Upper panel: Frequency distribution of Lden, calculated for the maximum façade point per respondent. Lower panel: Frequency distribution of IR_{24h} calculated at the façade point with the maximum Lden exposure. Figures on top of bars represent the absolute number of observations (respondents) within the respective category. Total cases: Road: N = 5431; Rail: N = 3536; Air: N = 3097.

r = 0.17 for road traffic, r = 0.73 for railway, and r = 0.74 for aircraft noise. These correlations are decidedly smaller than those usually observed between the most common noise metrics (like e.g. between Lden, Ldn, LDay, etc.). Because of the rather low correlation between Lden and IR_{24h} in the case of road traffic noise, we concluded that IR_{24h} could offer advantage as a complementary measure in noise effect exposure-response models particularly for road traffic noise.

3.3. Non-response analysis

A potential non-response bias was investigated by comparing the distributions of noise exposure and noise annoyance and a few further variables between all responders and a random sample of initial non-responders of Wave 3. From a total of 483 telephone calls that resulted in a successful contact, 224 persons agreed to be interviewed, giving a quite solid response rate of 46%. Regarding the reasons for initial non-response, 66% of the non-responders told the interviewer that they had “no time” to fill out the questionnaire, and only 7% that they were “not interested” in the survey. Table 1 shows means of responders and non-responders and results of Mann-Whitney-*U* Tests of differences between the two groups.

Table 1 shows that many of our ad hoc assumptions about non-responders could not be confirmed or were unsubstantiated, e.g. that non-responders are younger, or are significantly less annoyed than responders and therefore not interested to take part in noise surveys etc. There were no relevant differences between responders and non-responders regarding average noise exposure of all three sources. We thus conclude that people with elevated noise exposures were not more likely (or less likely) to take part in the survey. The same is true for noise annoyance, showing no significant difference between responders and non-responders. Regarding the variable age, we could observe a mean difference of 6 years between the two groups, with responders on average being younger than non-responders. Despite the usual observation that with increasing age, the willingness to take part in surveys (or the time to fill out questionnaires) normally increases, the opposite effect we found here could be explained with the different contact mode employed for the non-response interviews: The use of fixed line telephone interviews (as opposed to postal and online mode) may have decreased the chances to reach younger persons via telephone. While education level was only slightly higher in responders than non-responders, pro-environmental attitudes were even more frequent in non-responders (despite their higher average age). Expectedly, responders on average scored higher on noise sensitivity than non-responders.

3.4. %HA per Lden category

Elucidating the relationships between noise exposure and the percentage highly annoyed (%HA) which are representative for the average Swiss population affected by transportation noise was one of the main goals of the present study. Table 2 lists the observed %HA for each Lden category (in 5 dB steps). Fig. 2 shows observed mean %HA in ascending Lden categories.

3.5. Relationship between Intermittency Ratio IR and %HA

We hypothesized that IR might display a non-linear relationship regarding its association with the percentage of highly annoyed (%HA). Fig. 3 therefore shows predicted mean %HA in ascending categories of IR_{24h} for road, rail, and aircraft noise. The panels A1 to A3 in the top row show the results for a simple model not controlling for Lden, and the panels B1 to B3 show results of a model that includes Lden as covariate.

The panels A2 and A3 in Fig. 3 reveal that for railway and aircraft noise, annoyance is linearly associated with IR_{24h}, which is certainly a consequence of the considerable correlation between Lden and IR_{24h} in these noise sources. For road traffic noise (A1), a reversed U-like shape of the relationship becomes apparent. As panels B2 and B3 (models including Lden as predictor) demonstrate, the linear relationship in the railway and aircraft noise models almost disappears when the models adjust for Lden.

As indicated by the highest IR_{24h} category showing the lowest %HA value, upper categories of IR for road traffic noise (Fig. 3, Panel B1) may represent situations with fewer (but more emerging from background) distinct events and longer relatively quiet periods in between. We tested the potential explanation that lower annoyance might be the result of longer quiet periods by calculating the number of events contributing to the IR measure and deriving the average duration of event-free intervals (“pauses”) as a function of IR shown in Fig. 4. For all sources, but most distinctively for road traffic noise, pauses are shortest at medium IR and tend to be of longer duration at low and high IR. In accordance with the observations above, longer pauses (> 1–3 min) between noise events may decrease the annoyance potential of a road traffic noise exposure situation and hence could explain why annoyance at the same Lden level is lower at highly intermittent road traffic noise situations. For railway and aircraft noise, things are different: Pause durations for railway and aircraft noise are always longer than about 3 min (cp. Fig. 4 Panels B and C) and hence their actual duration may be not a relevant characteristic of a noise situation that would trigger annoyance reactions. This observation echoes an early laboratory study by Guski who found that subjects were only able to remember pauses within intermittent background noise while performing cognitive tasks, if the pauses had a duration of 3 or more minutes (Guski, 1988). The observation that very low IR values are associated with longer pauses too can be explained with the fact that in rather continuously emitting noise situations, individual peaking events, be they road, rail or aircraft pass-by events, are comparatively seldom and do not mark beginning and end of truly noise-free intervals. A “pause” in such contexts is not noise-free and, accordingly, would not reduce annoyance.

Table 1
Group means (+ standard deviation SD) and results of Mann-Whitney-*U* Tests of differences between responders and non-responders. Means of Lden figures are arithmetic means. Significant p's are highlighted in bold.

Variable	N Responders	N Non-responders	Mean (SD) Responders	Mean (SD) Non-responders	U	Z	p-Value
Lden road noise (most exp. façade point) [dB(A)]	5592	224	57.07 (8.94)	56.18 (9.37)	592,212.5	1.375	0.17
Lden railway noise (most exp. façade point) [dB(A)]	5592	224	36.34 (23.58)	34.73 (22.62)	597,711	1.152	0.25
Lden aircraft noise (most exp. façade point) [dB(A)]	5592	224	27.88 (24.40)	28.86 (24.12)	618,065	−0.325	0.75
Annoyance score road [11-pt scale]	5159	218	3.34 (2.90)	3.18 (2.87)	574,779.5	0.796	0.43
Annoyance score railway [11-pt scale]	5301	218	1.82 (2.71)	1.55 (2.63)	541,246	1.577	0.12
Annoyance score aircraft [11-pt scale]	5244	219	2.45 (2.93)	2.22 (2.66)	564,975.5	1.047	0.30
Age [years]	5304	211	48.91 (15.05)	55.20 (14.74)	447,170.5	−5.97	< **0.01**
Noise sensitivity [single item scale from 1 to 6]	5192	219	3.42 (1.60)	2.80 (1.40)	463,376	5.614	< **0.01**
Pro-environmental attitude [0(no)-1(yes)]	5312	166	0.66 (0.47)	0.76 (0.43)	398,717	−2.177	**0.03**
Education level [Scale from 1 to 13]	5455	209	6.76 (3.32)	6.24 (2.98)	524,295.5	1.972	**0.05**

Table 2
Observed %HA per Lden level category (Lden at the loudest façade point).

Lden [dB(A)]	Road			Rail			Air		
	# cases	% of sample	%HA	# cases	% of sample	%HA	# cases	% of sample	%HA
30–35	30	1%	3%	468	13%	1%	287	9%	1%
35–40	138	3%	2%	498	14%	1%	522	17%	2%
40–45	354	7%	2%	474	13%	1%	563	18%	3%
45–50	736	14%	4%	410	12%	4%	475	15%	8%
50–55	1005	19%	5%	393	11%	8%	434	14%	17%
55–60	1006	19%	10%	378	11%	11%	433	14%	34%
60–65	1033	19%	19%	370	10%	18%	271	9%	41%
65–70	813	15%	24%	299	8%	28%	108	3%	49%
70–75	267	5%	30%	197	6%	40%	3	0%	0%
75–80	48	1%	46%	45	1%	36%	1	0%	100%
> 80	1	0%	0%	4	0%	75%			

3.6. Exposure-response relationship for %HA

To derive exposure-response relationships for the outcome %HA, we regressed the probability of being highly annoyed (P_{HA}) on different sets of variables, referred to as Models 0 to 5 (cp. Section 2.6). Unstandardized (B) and standardized (β) coefficients, standard error of B (SE of B), and odds ratios (exp(B), per unit (1 dB) increase) are given in Table 3. Multicollinearity in the models was evaluated by means of a collinearity analysis based on logistic regression models excluding the quadratic terms age^2 and $IR_{24h}{}^2$. Resulting variance inflation factors (VIF) were < 5 in all predictors for all sources, which indicates that no serious multicollinearity problems were present (Table 3).

Results from Table 3 show Lden to be a significant predictor for noise annoyance in all models and through all levels of adjustment. Similarly, this was the case for IR_{24h} and $IR_{24h}{}^2$ for road traffic and railway noise. In the full model (Model 5), aircraft noise annoyance was negatively associated with road and railway noise exposure, which could be a consequence of the sound masking potential, at least in the case of road traffic, which would reduce aircraft noise annoyance, as demonstrated earlier by Lim et al. (2008). In contrast, railway and aircraft noise exposure did not influence road traffic noise annoyance in a relevant manner. The effect of access to a quiet side of the dwelling was expressed as exposure difference between the maximum and minimum façade point and this significantly reduced the probability to be highly annoyed by both road traffic and railway noise.

Survey language was associated with reported annoyance significantly only for aircraft noise, possibly explainable by specific differences of the noise soundscape between the main Swiss airports Geneva (in the French speaking part, with N = 772 valid responses) and Zurich (in the German speaking part, with N = 1947 valid responses) or any other local (e.g. political) peculiarities relating to aircraft noise issues. The survey mode (postal versus online) was not significantly associated with annoyance, and by adjusting for it, any remaining bias induced by survey mode should have been removed.

As expected, we also found a positive association with outside air temperature, which was significant in the road and railway models, corroborating earlier findings that annoyance tends to be higher in warmer seasons (Brink et al., 2016; Miedema et al., 2005).

In Table T4 (Supplementary section) we compared relevant goodness of fit statistics between all six models, using the Nagelkerke R^2, the Akaike Information Criterion (AIC), and the Hosmer-Lemeshow statistic (H-L). The addition of IR_{24h} and $IR_{24h}{}^2$ to the crude model (0) still resulted in a smaller AIC (despite the penalization of the additional number of predictors inherent in AIC) for all sources, which indicates that IR can explain marginal additional variance. Generally, the full model (Model 5) fits better and explains more variance for all noise sources. We observed that the road traffic Models 0–3 fit rather poorly, indicated by the significant or borderline significant H-L statistics (cp. T4). This observation is in line with a review on explained variance of exposure-annoyance relationships based on data from 41 annoyance surveys, where it was found that on average road traffic surveys yield smaller R^2 than railway or aircraft noise surveys (Brink, 2014). The reasons for this remain to be elucidated.

Fig. 5 (left) shows exposure-response curves for the three noise sources with dotted lines for the 95% CI. To visualize the effect of IR on %HA, Fig. 5 (right) plots %HA as a function of IR_{24h} for the two (arbitrarily chosen) Lden values of 45 and 65 dB(A).

Fig. 5 clearly reveals an association between Lden and %HA as well as a marked increase of %HA for railway and aircraft noise as compared to the so called “EU curves” from 2002 (European Commission, 2002) which are widely used for noise impact assessments in the EU and elsewhere. The %HA increase is particularly pronounced for aircraft

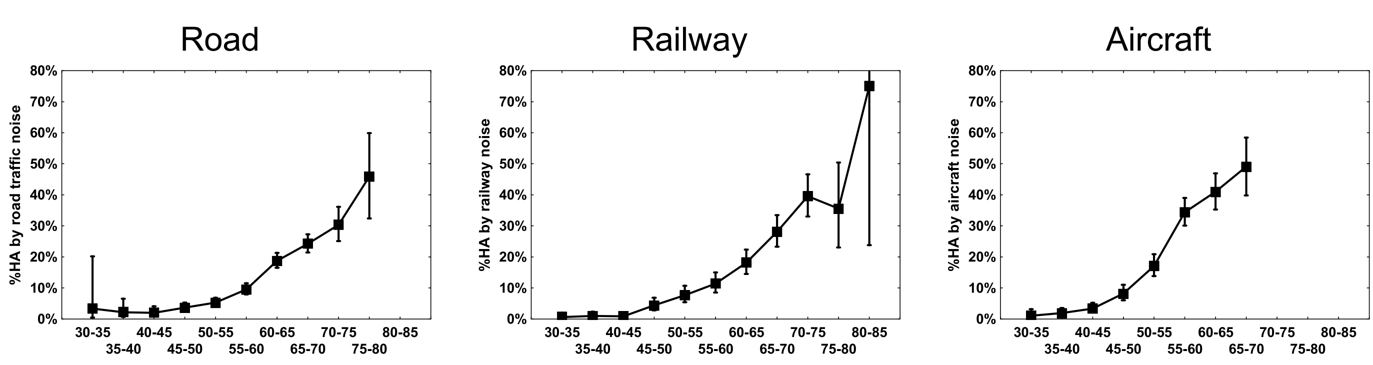

Fig. 2. Mean probability to be highly annoyed (expressed as %HA) in ascending categories of Lden for road, railway, and aircraft noise, including 95% CI.

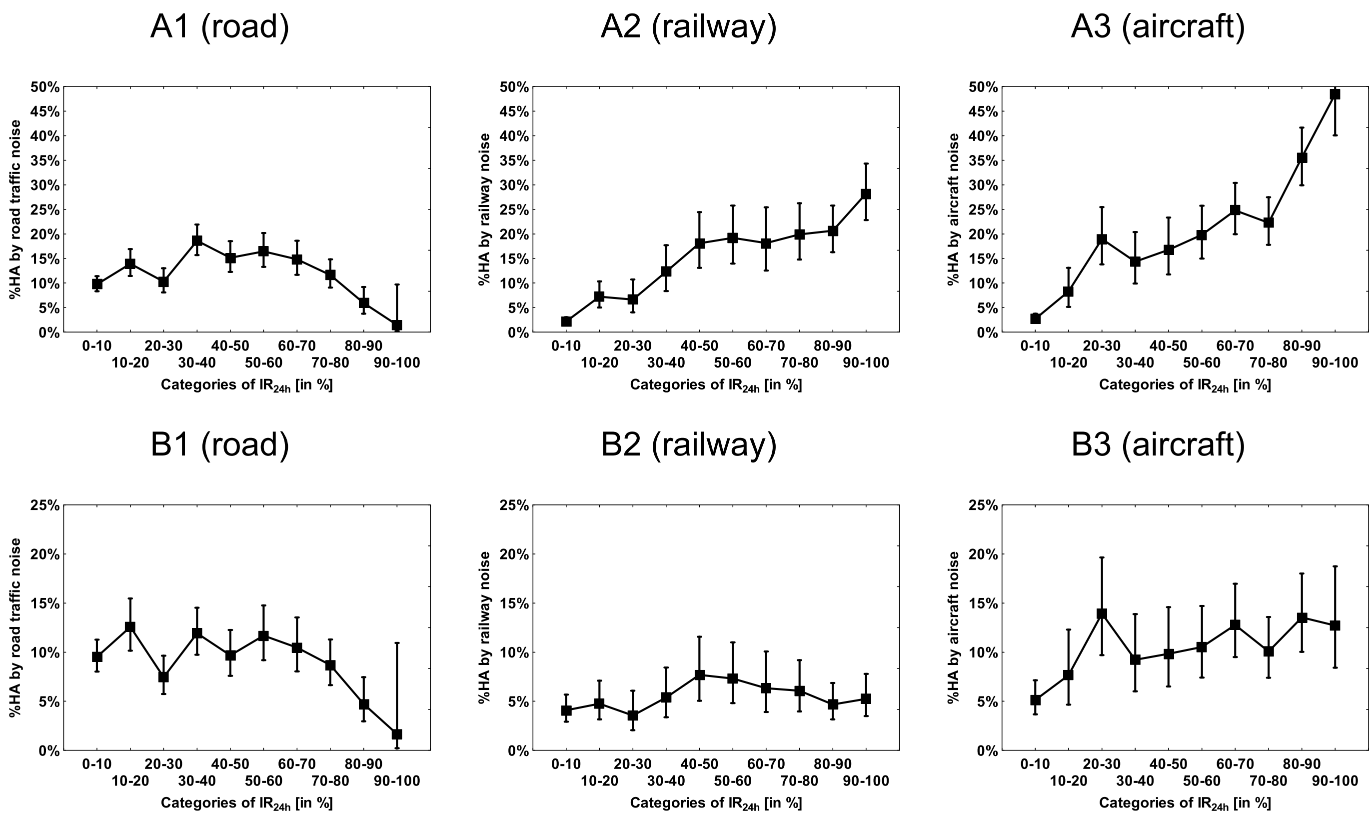

Fig. 3. Predicted %HA in ascending categories of IR_{24h}, for road, railway, and aircraft noise, including 95% CI. Panels A1-A3 include only the IR_{24h} category as predictor, Panels B1–B3 additionally include the Lden as predictor.

noise. The curve for aircraft noise is also higher than that from a previous Swiss study carried out in the vicinity of Zurich Airport back in 2001/2003 (Brink et al., 2008b). Contrary to expectation, railway noise exposure is associated with higher annoyance probability than road traffic noise.

In order that the exposure-response curves from Fig. 5 (left) can be used in other than Lden-related contexts (e.g. for impact assessments in countries not using Lden, or for meta-analyses), the coefficients of the logistic equations for the most often used noise metrics (Lden, Ldn, $L_{Aeq,24h}$, $LDay_{06\text{-}22h}$, and $LDay_{07\text{-}23h}$) are reported in Supplementary table T5. Coefficients are based on the fully adjusted model (i.e. all predictors from Model 5 used), but regressed on Ldn, $L_{Aeq,24h}$, $LDay_{06\text{-}22h}$, and $LDay_{07\text{-}23h}$, at the most exposed façade point, instead of on Lden.

3.7. Exposure-response relationships for different IR categories

Figs. 6–8 show the modeled relationship between Lden and %HA for three different (but arbitrarily chosen) levels of IR_{24h}, namely “low”, “midrange” and “high” (corresponding to IR values of 10%, 50%, and 90%). The curves were drawn based on the parameter estimates of the full model (Model 5, cp. Table 3).

In the case of road traffic noise (Fig. 6), where the correlation between Lden and IR_{24h} is relatively small, low levels of IR_{24h}, thus a more constant exposure pattern, clearly seems to elicit stronger HA reactions. In contrast, the general trend for railway and aircraft noise (Figs. 7 and 8) seems to be that midrange intermittency (IR_{24h} = 50%), leads to slightly higher values of %HA than low (IR_{24h} = 10%) or very high (IR_{24h} = 90%) intermittency. However, the shifts between exposure-

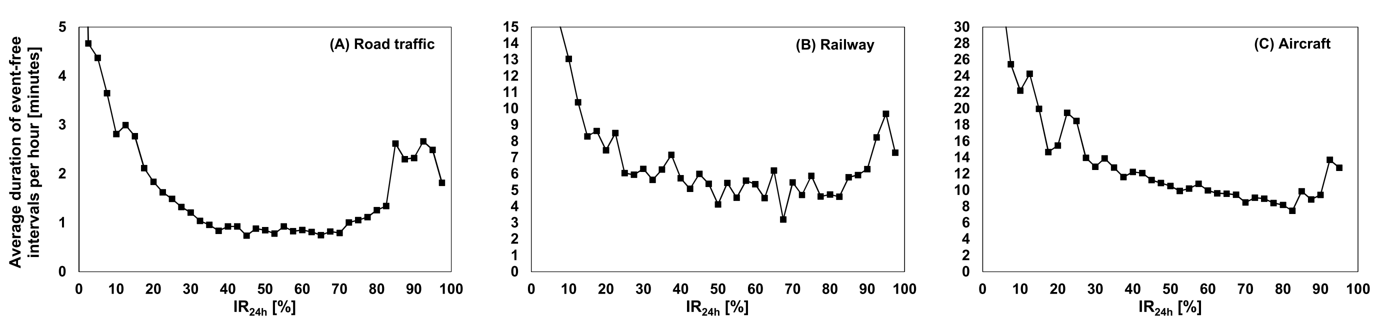

Fig. 4. Average duration of pauses (event-free intervals) in-between events per hour [in minutes] for road traffic (Panel A), railway (Panel B), and aircraft noise (Panel C). Note the different scales of the ordinate [minutes] axis.

Table 3

Coefficients of logistic regression models on the probability to be highly annoyed (P_{HA}), for road traffic, railway, and aircraft noise. Significant p's are highlighted in bold.

	Statistic	Intercept	Lden [dB (A)]	IR_{24h} [%]	$IR_{24h}{}^2$	Lden 2nd source [dB (A)]	Lden 3rd source [dB (A)]	Male sex (vs. female)	Age [years]	Age^2	German (vs. FR/IT)	Home owner (vs. tenant)	Education level	Duration at dwelling [Years]	Air temp. [°C]	Postal mode (vs. online)	Diff. Max-Min Facade
Road traffic noise[a]																	
Model 0	B	−8.1435	0.1038														
	SE of B	0.3555	0.0057														
	exp(B)	0.0000	1.1094														
	β	−2.2324	0.9218														
	VIF[1]		0.0000														
	p	**< 0.01**	**< 0.01**														
Model 1	B	−8.0943	0.1013	0.0155	−0.0002												
	SE of B	0.3561	0.0058	0.0059	0.0001												
	exp(B)	0.0000	1.1066	1.0156	0.9998												
	β	−2.2400	0.8993	0.4266	−0.5326												
	VIF[1]		1.0067	1.0067													
	p	**< 0.01**	**< 0.01**	**0.01**	**< 0.01**												
Model 2	B	−7.8440	0.1015	0.0147	−0.0002	−0.0003	−0.0054										
	SE of B	0.4286	0.0059	0.0060	0.0001	0.0034	0.0043										
	exp(B)	0.0000	1.1068	1.0148	0.9998	0.9997	0.9946										
	β	−2.2393	0.9011	0.4054	−0.5339	−0.0047	−0.0619										
	VIF[1]		1.0661	1.4012		1.4000	1.3327										
	p	**< 0.01**	**< 0.01**	**0.01**	**< 0.01**	0.92	0.20										
Model 3	B	−10.2316	0.1062					−0.1865	0.0839	−0.0008	−0.2158	0.0199	0.0084				
	SE of B	0.6439	0.0059					0.0878	0.0211	0.0002	0.0891	0.0981	0.0131				
	exp(B)	0.0000	1.1121					0.8298	1.0875	0.9992	0.8059	1.0201	1.0085				
	β	−2.2641	0.9431					−0.0931	1.2529	−1.1308	−0.1020	0.0096	0.0279				
	VIF		1.0269					1.0123	1.1393	0.0000	1.0086	1.1127	1.0539				
	p	**< 0.01**	**< 0.01**					**0.03**	**< 0.01**	**< 0.01**	**0.02**	0.84	0.52				
Model 4	B	−10.0984	0.1037	0.0157	−0.0002	0.0014	−0.0049	−0.1830	0.0853	−0.0008	−0.1939	0.0859	0.0071				
	SE of B	0.6865	0.0061	0.0061	0.0001	0.0035	0.0044	0.0881	0.0212	0.0002	0.0913	0.1002	0.0132				
	exp(B)	0.0000	1.1093	1.0158	0.9998	1.0014	0.9951	0.8328	1.0890	0.9992	0.8238	1.0897	1.0071				
	β	−2.2697	0.9209	0.4333	−0.5514	0.0189	−0.0558	−0.0913	1.2742	−1.1518	−0.0916	0.0412	0.0234				
	VIF[1]		1.0968	1.4470		1.4340	1.3698	1.0142	1.1402		1.0481	1.1424	1.0558				
	p	**< 0.01**	**< 0.01**	**0.01**	**< 0.01**	0.70	**0.03**	**0.04**	**< 0.01**	**< 0.01**	**0.03**	0.39	0.59				
Model 5	B	−10.6891	0.1108	0.0176	−0.0002	0.0001	−0.0032	−0.1891	0.0876	−0.0008	−0.1785	0.0867	0.0024	0.0004	0.0188	−0.0532	−0.0160
	SE of B	0.7264	0.0069	0.0062	0.0001	0.0036	0.0045	0.0215	0.0215	0.0002	0.0930	0.1026	0.0134	0.0043	0.0063	0.1096	0.0072
	exp(B)	0.0000	1.1172	1.0178	0.9998	1.0001	0.9968	0.9992	1.0916	0.9992	0.8366	1.0906	1.0024	1.0004	1.0190	0.9482	0.9841
	β	−2.2794	0.9841	0.4851	−0.5726	0.0009	−0.0368	−0.0944	1.3091	−1.1844	−0.0843	0.0416	0.0079	0.0056	0.1325	−0.0216	−0.1143
	VIF[1]		1.3683	1.5205		1.4964	1.3961	1.0335	1.4783		1.0764	1.1844	1.0764	1.4691	1.0171	1.0768	1.4448
	p	**< 0.01**	**< 0.01**	**< 0.01**	**< 0.01**	0.99	0.47	**0.03**	**< 0.01**	**< 0.01**	0.06	0.06	0.86	0.92	**< 0.01**	0.63	**0.03**

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Table 3 (*continued*)

	Statistic	Intercept	Lden [dB (A)]	IR_{24h} [%]	IR_{24h}^2	Lden 2nd source [dB (A)]	Lden 3rd source [dB (A)]	Male sex (vs. female)	Age [years]	Age^2	German (vs. FR/IT)	Home owner (vs. tenant)	Education level	Duration at dwelling [Years]	Air temp. [°C]	Postal mode (vs. online)	Diff. Max-Min Facade
Railway noise[b]																	
Model 0	B	−8.6611	0.1138														
	SE of B	0.3905	0.0062														
	exp(B)	0.0000	1.1205														
	β	−2.9609	1.4379														
	VIF[1]		0.0000														
	p	< **0.01**	< **0.01**														
Model 1	B	−8.6014	0.1059	0.0223	−0.0002												
	SE of B	0.4313	0.0080	0.0088	0.0001												
	exp(B)	0.0000	1.1117	1.0225	0.9998												
	β	−3.0119	1.3384	0.7314	−0.5687												
	VIF[1]		1.6114	1.6114													
	p	< **0.01**	< **0.01**	**0.01**	**0.02**												
Model 2	B	−8.2951	0.1153	0.0190	−0.0002	−0.0138	0.0026										
	SE of B	0.6261	0.0110	0.0092	0.0001	0.0109	0.0065										
	exp(B)	0.0000	1.1222	1.0192	0.9998	0.9863	1.0026										
	β	−3.0248	1.4572	0.6242	−0.5642	−0.1213	0.0288										
	VIF[1]		2.9993	3.7285		2.3342	1.1077										
	p	< **0.01**	< **0.01**	**0.04**	**0.02**	0.21	0.69										
Model 3	B	−9.8027	0.1146					−0.0612	0.0318	−0.0003	0.0539	0.2282	0.0243				
	SE of B	0.7965	0.0063					0.1252	0.0283	0.0003	0.1348	0.1408	0.0191				
	exp(B)	0.0000	1.1215					0.9406	1.0323	0.9997	1.0553	1.2563	1.0246				
	β	−2.9604	1.4484					−0.0306	0.4776	−0.3909	0.0249	0.1068	0.0809				
	VIF		1.0222					1.0161	1.1363	0.0000	1.0060	1.1147	1.0465				
	p	< **0.01**	< **0.01**					0.6249	0.2608	0.3573	0.6895	0.1050	0.2036				
Model 4	B	−9.3973	0.1143	0.0186	−0.0002	−0.0112	0.0010	−0.0457	0.0314	−0.0003	0.0196	0.2012	0.0236				
	SE of B	0.9469	0.0110	0.0093	0.0001	0.0110	0.0066	0.1252	0.0282	0.0003	0.1360	0.1418	0.0191				
	exp(B)	0.0000	1.1211	1.0188	0.9998	0.9888	1.0011	0.9553	1.0319	0.9997	1.0198	1.2228	1.0238				
	β	−3.0196	1.4448	0.6119	−0.5375	−0.0990	0.0117	−0.0228	0.4713	−0.3832	0.0090	0.0942	0.0785				
	VIF[1]		3.0075	3.7018		2.3353	1.1033	1.0166	1.1370		1.0203	1.1341	1.0490				
	p	< **0.01**	< **0.01**	0.05	**0.03**	0.31	0.88	0.71	0.27	0.37	0.89	0.16	0.22				
Model 5	B	−10.7056	0.1408	0.0218	−0.0002	−0.0243	0.0014	−0.0201	0.0344	−0.0003	0.0345	0.1771	0.0298	0.0061	0.0268	0.2528	−0.0366
	SE of B	1.0159	0.0140	0.0095	0.0001	0.0119	0.0067	0.0289	0.0289	0.0003	0.1389	0.1466	0.0196	0.0062	0.0089	0.1639	0.0117
	exp(B)	0.0000	1.1511	1.0221	0.9998	0.9760	1.0014	0.9997	1.0350	0.9997	1.0351	1.1938	1.0303	1.0061	1.0271	1.2876	0.9641
	β	−3.0246	1.7785	0.7168	−0.6581	−0.2142	0.0152	−0.0100	0.5175	−0.4810	0.0159	0.0829	0.0994	0.0746	0.1873	0.1040	−0.4185
	VIF[1]		4.9854	3.8201		2.6769	1.1069	1.0335	1.4833		1.0383	1.1796	1.0688	1.4859	1.0142	1.0919	2.7016
	p	< **0.01**	< **0.01**	**0.02**	**0.01**	**0.04**	0.84	0.88	0.23	0.27	0.80	0.80	0.13	0.32	< **0.01**	0.12	< **0.01**

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Table 3 (*continued*)

Aircraft noise[c]

	Statistic	Intercept	Lden [dB (A)]	IR_{24h} [%]	IR_{24h}^2	Lden 2nd source [dB (A)]	Lden 3rd source [dB (A)]	Male sex (vs. female)	Age [years]	Age^2	German (vs. FR/IT)	Home owner (vs. tenant)	Education level	Duration at dwelling [Years]	Air temp. [°C]	Postal mode (vs. online)
Model 0	B	−9.1120	0.1420													
	SE of B	0.4008	0.0072													
	exp(B)	0.0000	1.1526													
	β	−2.3460	1.3751													
	VIF[1]		0.0000													
	p	< **0.01**	< **0.01**													
Model 1	B	−8.6338	0.1210	0.0248	−0.0002											
	SE of B	0.4543	0.0093	0.0075	0.0001											
	exp(B)	0.0000	1.1286	1.0251	0.9998											
	β	−2.4162	1.1716	0.8236	−0.4863											
	VIF[1]		1.6486	1.6486												
	p	< **0.01**	< **0.01**	< **0.01**	**0.02**											
Model 2	B	−7.3641	0.1524	0.0116	−0.0001	−0.0322	−0.0160									
	SE of B	0.5366	0.0125	0.0082	0.0001	0.0094	0.0055									
	exp(B)	0.0000	1.1647	1.0117	0.9999	0.9684	0.9841									
	β	−2.4972	1.4764	0.3860	−0.3754	−0.2848	−0.2095									
	VIF[1]		2.7729	2.9389		1.9282	1.0958									
	p	< **0.01**	< **0.01**	0.16	0.07	< **0.01**	< **0.01**									
Model 3	B	−10.1069	0.1421					−0.0468	0.0296	−0.0002	−0.3259	0.4541	0.0315			
	SE of B	0.8105	0.0077					0.1166	0.0272	0.0003	0.1234	0.1266	0.0180			
	exp(B)	0.0000	1.1527					0.9543	1.0300	0.9998	0.7219	1.5747	1.0320			
	β	−2.3916	1.3762					−0.0233	0.4419	−0.3421	−0.1428	0.2136	0.1067			
	VIF		1.0774					1.0176	1.1322	0.0000	1.0506	1.1288	1.0780			
	p	< **0.01**	< **0.01**					0.6883	0.2764	0.3951	< **0.01**	< **0.01**	0.0797			
Model 4	B	−8.4869	0.1490	0.0137	−0.0001	−0.0275	−0.0135	−0.0220	0.0261	−0.0002	−0.3003	0.3887	0.0283			
	SE of B	0.8941	0.0130	0.0084	0.0001	0.0097	0.0056	0.1168	0.0271	0.0003	0.1250	0.1277	0.0180			
	exp(B)	0.0000	1.1606	1.0138	0.9999	0.9729	0.9866	0.9783	1.0264	0.9998	0.7406	1.4751	1.0287			
	β	−2.5301	1.4428	0.4544	−0.4060	−0.2433	−0.1772	−0.0109	0.3896	−0.2959	−0.1316	0.1829	0.0958			
	VIF[1]		2.8920	2.9601		1.9456	1.1106	1.0200	1.1288		1.0710	1.1472	1.0784			
	p	< **0.01**	< **0.01**	0.10	0.06	< **0.01**	0.92	0.85	0.34	0.46	**0.02**	< **0.01**	0.12			
Model 5	B	−8.7014	0.1496	0.0127	−0.0001	−0.0272	−0.0136	−0.0113	0.0316	−0.0003	−0.2734	0.3627	0.0275	0.0036	0.0058	−0.0546
	SE of B	0.9274	0.0131	0.0085	0.0001	0.0097	0.0057	0.0276	0.0276	0.0003	0.1280	0.1299	0.0183	0.0058	0.0082	0.1442
	exp(B)	0.0000	1.1613	1.0128	0.9999	0.9732	0.9865	0.9997	1.0321	0.9997	0.7608	1.4372	1.0278	1.0036	1.0058	0.9468
	β	−2.5281	1.4485	0.4232	−0.3756	−0.2405	−0.1778	−0.0056	0.4719	−0.3948	−0.1198	0.1707	0.0931	0.0437	0.0405	−0.0227
	VIF[1]		2.8735	2.9433		1.9488	1.1132	1.0408	1.5185		1.1110	1.1756	1.1018	1.5253	1.0147	1.0745
	p	< **0.01**	< **0.01**	0.13	0.08	**0.01**	**0.02**	0.92	0.25	0.34	**0.03**	**0.03**	0.13	0.53	0.48	0.70

[a] 2nd source: railway; 3rd source: aircraft.
[b] 2nd source: road; 3rd source: aircraft.
[c] 2nd source: road; 3rd source: railway.
[1] Variance inflation factor.

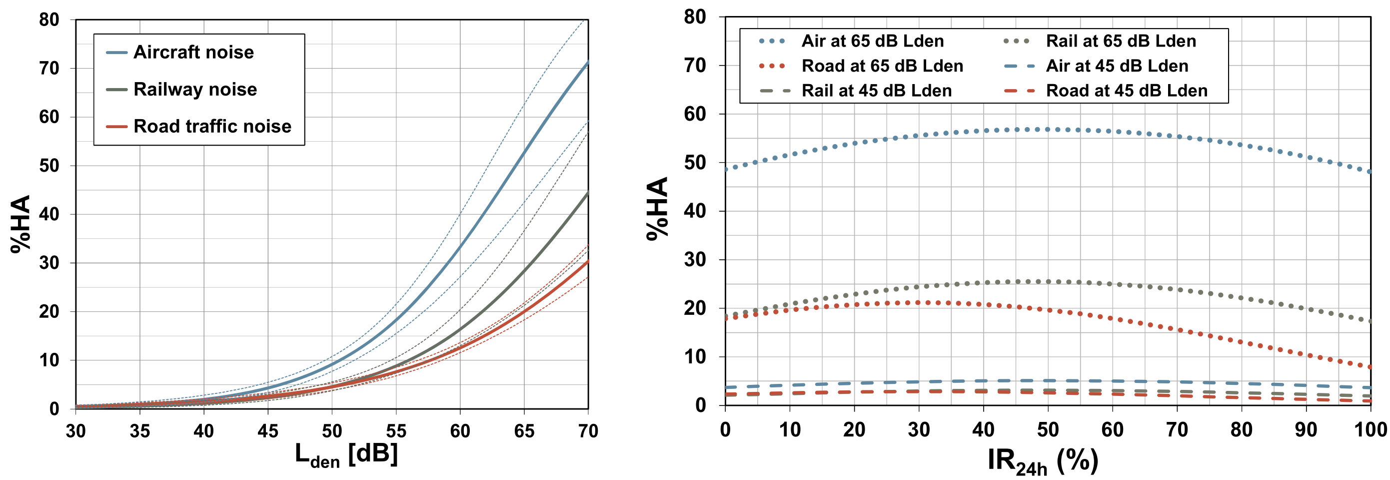

Fig. 5. Left: Exposure-response curves for the percentage highly annoyed (%HA) by road, rail, and aircraft noise, including 95% CI. The curves are based on Model 5 with all covariates centered on the mean. Right: Percentage highly annoyed (%HA) by road, rail, and aircraft noise as function of IR_{24h} for two different Lden values (45 and 65 dB(A)).

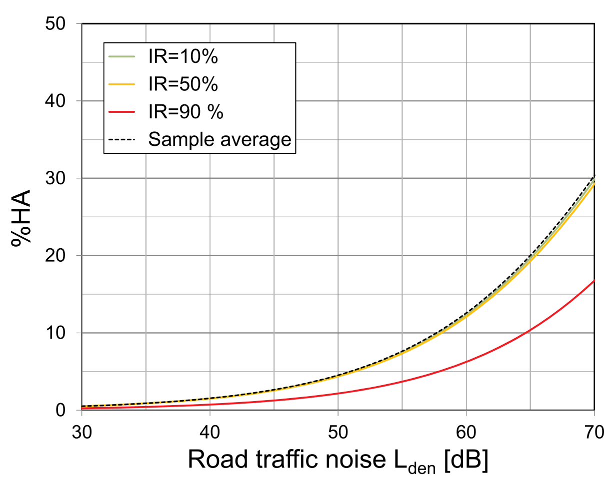

Fig. 6. Modeled percentage highly annoyed (%HA) by road traffic noise for three different IR_{24h} values (10%, 50%, 90%) and for the sample average of IR_{24h}. The curves are based on the full model with covariates centered on the mean. For better visibility, confidence interval boundaries are not shown.

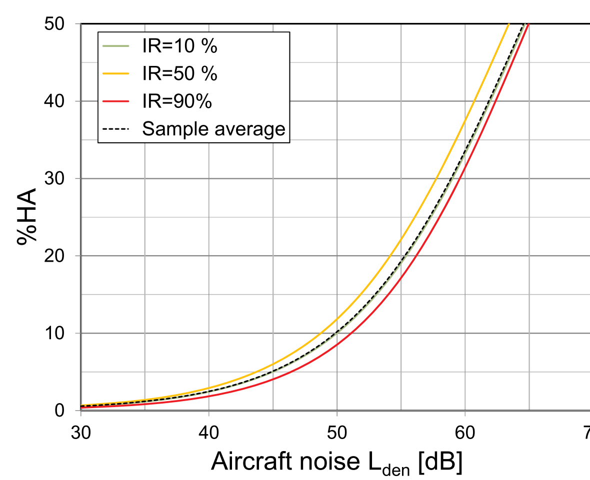

Fig. 8. Modeled percentage highly annoyed (%HA) by aircraft noise for three different IR_{24h} values (10%, 50%, 90%) and for the sample average of IR_{24h}. The curves are based on the full model with covariates centered on the mean. For better visibility, confidence interval boundaries are not shown.

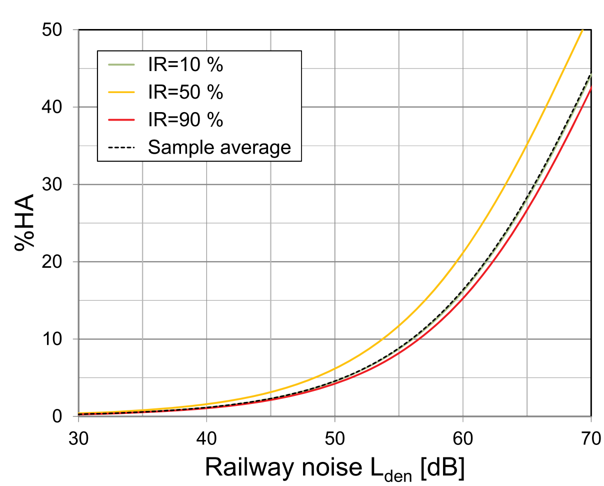

Fig. 7. Modeled percentage highly annoyed (%HA) by railway noise for three different IR_{24h} values (10%, 50%, 90%) and for the sample average of IR_{24h}. The curves are based on the full model with covariates centered on the mean. For better visibility, confidence interval boundaries are not shown.

response curves brought about by very different intermittency characteristics are relatively small for rail and air traffic (about 2–3 dB difference between the IR_{24h} = 10% and IR_{24h} = 90% -curves), but markedly more pronounced (about 6 dB) for road traffic noise.

4. Discussion

4.1. Synthesis

The present study established exposure-response relationships reflecting the percentage highly annoyed (%HA) by road, railway, and aircraft noise in a representative sample of the Swiss population. Results (cp. Table 3) clearly revealed an association between Lden and %HA for all noise sources investigated, which remained positive and statistically significant across all levels of adjustment. We observed a marked difference of %HA for railway and aircraft noise as compared to the EU standard curves (European Commission, 2002), corroborating findings that annoyance to these sources has increased in the last decades (Guski, 2017). Aircraft noise annoyance scored markedly higher than annoyance to road traffic and railway noise at the same Lden level.

Railway noise elicited slightly higher percentages of highly annoyed persons than road traffic noise. Aircraft noise annoyance decreased significantly with increasing road traffic and railway noise exposure, pointing to a potential sound masking effect of the latter two sources. We could also demonstrate that annoyance decreased with increasing sound level difference between the loudest and the faintest facade point of the dwelling. Residents thus seem to benefit from having a quiet side on their house or apartment. Furthermore, %HA, depending on noise source, showed significant association with age (older respondents being more annoyed), outside temperature before the date of fill-out (higher temperatures associated with higher percentages of HA), home ownership (owners being more annoyed by aircraft noise), and intermittency of the noise source, details of which are discussed below.

The metric Intermittency Ratio (IR) quantifies the energetic contribution of individual noise events above the background level to the total noise exposure. Initially, we hypothesized that highly intermittent noise has more potential to disturb certain activities and thus would also foster stronger annoyance reactions. While this was confirmed by somewhat higher %HA in highly intermittent rail and aircraft noise, we found that IR_{24h} has the opposite effect on road traffic noise annoyance: For road traffic noise, exposure situations with low IR_{24h} (most certainly motorways) were associated with HA responses that were > 6 dB higher than situations with high IR_{24h} (cp. Fig. 6). This observation is in line with other studies that investigated annoyance differences between motorways and city streets (Danish Road Directorate, 2016; Miedema, 1993), but contradicts results reported by (Lercher et al., 2008), who found the opposite. However, the latter study was carried out in the rather special environment of an alpine valley which might constitute a very specific case.

4.2. Strengths and limitations

To our knowledge, this is the first noise annoyance survey that used a systematic approach to parametrize the degree of discontinuity/intermittency of noise exposure calculated from traffic data and implemented this parameter in a nation-wide noise exposure database. The employed stratification and wide range of exposure levels incident at each individual dwelling provided optimal exposure contrast and equally sized cells that are necessary to derive empirically sound exposure-response relationships. The spatial and temporal expansion of the survey in serveral time-separated waves and in all corners of the country is an important asset of the study as this prevented getting biased annoyance responses that could have been triggered by time-specific or site-related effects like e.g. local noise policy and its coverage in the media or sudden changes in local transportation infrastructure etc. On the same note, noise exposure calculations have been carried out with unprecedented spatial and temporal resolution, allowing e.g. to calculate the difference between the most exposed and the quietest façade point of a dwelling unit, and this not only for one noise metric (e.g. Lden), but for 24 1-h Leq values which allowed to provide exposure-response functions for most relevant noise metrics in use today (cp. Supplementary table T5).

Seasonal differences in annoyance responses reported earlier (Brink et al., 2016; Miedema et al., 2005) were accounted for by running four survey waves at different times of the year, and outdoor temperature was individually assigned and included as predictor to produce exposure-response relationships representing the average effect of noise exposure throughout a year.

A few limitations pertaining to certain conceptual problems inherent in IR, response rate, and the adequacy of exposure assessment remain to be mentioned:

It is in the nature of the calculation of source-specific IR, that its value depends on the overall background level produced by other transportation noise sources present at the receiver point, (cp. Wunderli et al., 2015). If their exposure is relatively high, source specific IR can drop to very low values even if the target (primary) source can still be considered "eventful". Thus, a low IR of a primary source (e.g. railway noise) could simply mean that other sources (e.g. road traffic noise) masked many of the individual events of the primary source. Furthermore, IR and Lden are always correlated to some degree, as has particularly been shown for railway and aircraft noise, with consequences for statistical model building. Solving the inherent interpretation problems emanating from these limitations will be one task to tackle in the future development of the IR metric.

The survey response rate of 31% achieved was rather moderate by earlier social science standards (but was well in the expected range). Decreasing response rates in surveys in the last decades are supported by solid data documenting this trend (e.g. Lepkowski et al., 2008). To counteract any selection bias in the survey sample, several precautionary measures have been taken. First, we essentially eliminated undercoverage within the sampling frame, as the survey sample was randomly drawn from official register data (that covered the full population) instead of e.g. telephone directories or voter registers. Regarding external validity, the most relevant question is if the modeled probability to be highly annoyed was biased towards an increased annoyance prevalence, as it can be hypothesized that any survey about noise will attract rather noise sensitive or noise annoyed persons to take part. We therefore, secondly, assessed the effect of non-response by carrying out a non-response study with initial non-responders. The non-response analyses did not suggest that responders were significantly different from nonresponders in the distribution of the primary variables of interest, which are road, rail and air traffic noise annoyance. It is of course possible that noise annoyed persons were potentially more likely to respond to both the survey *and* the non-response study. This could point to an overestimation of the prevalence of highly annoyed persons in the population despite the non-response interviews showed no difference between responders and initial non-responders. This is a limitation shared with practically all other studies of similar type. Thirdly, in order to increase response we employed a mixed-mode survey design (Dillman et al., 2009). The choice offered of either filling out the questionnaire in its paper-and-pencil form or online probably increased the response rate without introducing bias as there were no significant annoyance differences between online and postal responders (cp. Table 3). In summary, we cautiously conclude that the prevalence of noise annoyance in the underlying population was not overestimated in the survey and that the results, especially Model 5 with centered covariates (cp. Fig. 5 left), are representative for Switzerland. However, there might be residual bias in the sample insofar as noise sensitive people were on average a bit more likely to respond.

For the entire SiRENE project as a whole, noise exposure for all Swiss buildings and dwelling units was calculated for the reference year 2011. Hence there was a gap between the reference year of noise exposure calculations and the years the survey waves were carried out (2014 and 2015). For road traffic and railway noise exposure, slight alterations in local traffic from one year to the next on an established road/rail network have practically no effect on average yearly exposure. E.g. an increase in traffic by 20% leads to just about 1 dB increase in exposure level. However, changing flight routings, in the present case between 2011 and 2014, could have lead to not fully up-to-date aircraft noise exposure assignments.

5. Conclusions

This study evaluated the association between Lden and the percentage of highly annoyed persons for transportation noise in a representative stratified sample of the Swiss population. Its results primarily serve health impact assessment of road, railway, and aircraft noise and the setting of source-specific noise exposure limits. Aircraft noise was found to be a particularly annoying source, followed by railway, and road traffic noise. Our results point to the conclusion that a "railway bonus" (i.e. the usually less strong rating of railway noise as compared to road traffic noise) does not find empirical support, at least not in Switzerland, despite the fact that this country is known for its overly railway-friendliness.

A particular asset of this study's noise exposure modeling is the provision of temporal noise exposure characteristics in the form of the metric Intermittency Ratio (IR), in addition to Lden. As in the present sample, road traffic noise occurred in very different temporal patterns, from relative continuity to high intermittency, the inclusion of the IR metric in the exposure-response model for %HA could explain differences of > 6 dB between road traffic noise exposure situations with low (10%) or rather high (90%) IR_{24h} (cp. Fig. 6). We could thus show that the temporal distribution of sound energy from road traffic noise probably has an influence on annoyance reactions and therefore could be considered in the rating of road traffic noise in the future. However, the predictive value of using IR in the modeling of %HA was less strong in the case of railway noise (Fig. 7). Finally, IR was not linked to aircraft noise annoyance after full statistical adjustment.

In the present study, the occurrence of longer pauses in highly-intermittent road traffic scenarios may have been one relevant factor for the reduced annoyance in situations where single events, even if perceived as loud, are followed by periods of relative calmness. One avenue for future research in this context, or for the further development of the IR metric, could be the investigation of the trade-offs between number, duration and profoundness of phases of respite in an otherwise noise-burdened environment.

The authors declare no conflict of interest.

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Appendix A. Supplementary tables

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envint.2019.01.043.

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